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16. ABSTRACT

The inherent variability of 10- to 60-min average ground-level plume centerline concentrations in the wake of buildings and inherent limitations on the performance of a Gaussian plume model are presented. Point comparisons between observed and model-predicted concentrations were evaluated for three sets of field measurements. The presentation here is based on a quantitative evaluation of the same model that was qualitatively evaluated in a companion presentation (Huber, 1984). The same method prescribed for estimating enhanced dispersion in the wake of buildings and its incorporation into the Gaussian plume equation is used here. A sample of performance measures is judged to provide an adequate basis for determining the strengths and weaknesses of the model. Concentrations were partitioned into groups by source-receptor distance, atmospheric stability classification, and source-release height, which provide a way of identifying possible sources of variability and error. The baseline model was adjusted to provide some contrast for assessing model performances and to help identify possible areas for model improvement. For groups with reduced measures of mean error, the variability among errors was reduced to values between 50 and 100 percent of the mean concentration, which appears here to represent the inherent limitation of a simple Gaussian plume model.

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PERFORMANCE OF A GAUSSIAN MODEL FOR CENTERLINE CONCENTRATIONS IN THE WAKE OF BUILDINGS

ALAN H. HUBER*

Atmospheric Sciences Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711, U.S.A.

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Abstract—This paper examines the performance and inherent limitations of a Gaussian plume model for predicting ground-level plume centerline concentrations in the wake of buildings. The Gaussian plume equation has been modified to incorporate building wake enhanced dispersion parameters. Model-predicted concentrations were compared to three sets of field observations. Predicted and observed concentrations were partitioned into groups by source–receptor distance, atmospheric stability class, and source-release height. The group analyses provided a way to identify sources of model error. The variability of errors was found to have values between 50 and 100% of the mean observed concentration for groups where the mean error was small.

Key word index: Air quality models, model evaluation, building wake effects, atmospheric dispersion.

1. INTRODUCTION

Gaussian plume models are routinely applied in studies of environmental impact. They are most appropriately applied to situations having uncomplicated transport and diffusion between the source and receptors. Most of these models require only that a wind speed, emission rate, emission height, source–receptor distance, plume rise, and atmospheric stability class be known. Gaussian plume models perform best when estimating mean concentrations over time where mean values of the input parameters are representative.

This paper examines the performance and inherent limitations of some Gaussian plume models for predicting ground-level plume centerline concentrations in the wake of buildings. The model-predicted concentrations were calculated using the basic Gaussian plume model, modified to incorporate enhanced dispersion parameters in various ways. Discussions on the application of the specific model used here and the results of a qualitative model evaluation study of ground-level plume centerline concentrations for 10 sets of field observations were presented by Huber (1984). In that study, field measurements were mapped on plots of model-predicted concentrations. Point comparisons between observed and predicted concentrations were not evaluated. In a few cases, the mean of a group of observed concentrations was compared to the predicted concentration. These evaluations proved to be particularly suited to a qualitative assessment of the applicability of the model. In the analyses reported here, the three most complete sets of field observations and model predictions were further examined. The additional analyses provide a look into both the mean and variation among ground-level plume centerline concentrations, model predictions, and their differences (i.e. model error). The inherent limitations on the performance of a Gaussian plume model were examined.

The field data were taken from reports of three studies: (1) Thuillier and Mancuso (1980) at the Duane Arnold Energy Center (DAEC), Palo, Iowa; (2) Start *et al.* (1980) at the EOCR test reactor building, Idaho National Engineering Laboratory, in southeast Idaho; and (3) Engineering-Science (1980) at the natural gas compressor site 1 (NGC1) in south Texas.

The original field data bases were first screened to eliminate cases for which there were incomplete meteorological data or questionable centerline concentrations. The EOCR data were additionally screened to eliminate cases in which there was very large wind meander. For the DAEC and NGC1 studies, the reported Pasquill–Gifford (Turner, 1970) atmospheric stability classes A–F were used in the analysis. For the EOCR study, the reported Pasquill–Gifford stability classes A–F, based on the NRC vertical temperature change scheme, were reformatted into groups by wind speed and time of day to be more comparable to the stability categorizations of the other studies. In the DAEC data base, there were primarily unstable classes A–B (70%) and stable class E (18%). The stability classes for the EOCR study were primarily class C for later morning situations (33%) and class E for light wind early morning situations (53%). The stability

* On assignment from National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

classes for NGC1 study were neutral classes C–D (74%) with the remainder unstable class B.

All three field studies were conducted at sites having generally level terrain. The release heights and source–receptor distances were low enough so that the atmospheric mixing depth was not important. The source emission conditions were generally constant for each test. A full description of each field site and the experimental conditions are reported in the field study reports. A brief description of relevant field conditions is also presented in Huber (op. cit.).

The observed concentrations (χ) were normalized by the observed mean wind speed (U) at the release height and the observed emission rate (Q) so that $\chi U/Q$ ($m^{-2}10^{-6}$) was the observed value to be compared to the model-predicted value. The Gaussian plume model equation for the normalized ground-level centerline concentration is

$$\frac{\chi U}{Q} = \frac{\exp[(-1/2)(H/\sigma_z)^2]}{\pi\sigma_y\sigma_y} \ (m^{-2})$$

where

H = plume centerline height

σ_y, σ_z = the values of the horizontal and vertical dispersion parameters (i.e. standard deviation of plume profile that is presumed to have a Gaussian concentration distribution).

The plume centerline heights for the DAEC and the EOCR studies were set to the release height since vertical source momentum flux and source buoyancy flux were insignificant. The plume centerline height for the NGC1 study was set by adding estimated plume rise (Briggs, 1975) to the release height. Since the studied source emission conditions were generally fixed, the estimated mean plume centerline height for the NGC1 study was primarily a function of source–receptor distance, mean wind speed, and atmospheric stability. Buoyancy flux was not a significant factor. The building enhanced dispersion parameters were prescribed as in Huber (op. cit.)

$$\sigma'_y = 0.7\,W_b/2 + 0.067\,(x - 3H_b); \quad \text{for } 3H_b < x < 10H_b$$

$$\sigma'_z = 0.7\,H_b + 0.067\,(x - 3H_b); \quad \text{for } 3H_b < x < 10H_b$$

$$\sigma'_y(@\,x) = \sigma_y(@\,x + S_y); \text{ for } x \geqslant 10H_b$$

$$\sigma'_z(@\,x) = \sigma_z(@\,x + S_z); \text{ for } x \geqslant 10H_b$$

where

$W_b/2$ = "half-width" of the region of influential buildings normal to the wind,

H_b = height of highest influential building,

S_y = the virtual source distance such that $\sigma'_y(@\,10H_b) = 0.7\,W_b/2 + 0.5H_b$,

S_z = the virtual source distance such that $\sigma'_z(@\,10H_b) = 1.2H_b$

x = source–receptor distance.

Both enhanced horizontal and vertical dispersion parameters were incorporated into the model estimates, for the DAEC, EOCR, and the shorter NGC1 sources. The taller NGC1 source was modeled with only enhanced vertical dispersion parameters. The representative building heights and widths were the same as prescribed in the previous study. The dispersion parameters were a function of building scales, source–receptor distance, and atmospheric stability.

The model predictions of ground-level centerline pollution concentrations used here are only a function of mean wind speed, mean emission rate, source–receptor distance and atmospheric stability. The concentrations from each study were separately evaluated. This allowed a consideration of the uniqueness of each field site, field study design and field study performance. Within each study, the concentrations were partitioned into groups categorized by stability class (STAB), release height (HS), and source–receptor distance (X). The model predictions were compared to measured field conentrations paired in time and paired in space (i.e. assumed observed centerline vs modeled centerline at fixed source-receptor distance). In the normalized form, $\chi U/Q$, the model-predicted concentrations were constant for fixed source–receptor distance, plume height and atmospheric stability classification. The observed concentrations were naturally variable. Thus, this form of the observed concentrations provided a strong foundation for assessing inherent limitations of the model.

Single discrete release heights were used for the DAEC and EOCR studies since plume rise was insignificant. For the NGC1 study, plume height was a function of wind speed and downwind distance, which added to the variation among concentrations. The partitioning of the data by discrete STAB separated the data into groups with similar wind speed and thermal stratification. The assigned STAB fixed the estimated dispersion parameters σ_y and σ_z in each study. Such a discontinuous characterization of dispersion eliminated the variability among like model predictions, but led to greater variability of differences between predicted and observed concentrations because the atmosphere was not so discretely ordered. Atmospheric dispersion is a function of all temporal and spatial scales of motion in the atmosphere. Since discrete stability classification schemes have their limitations for characterizing dispersion, variability among observed concentrations cannot be entirely reflected by the model predictions.

The tabulated results presented in the following section summarize the key performance measures for this evaluation of the above proposed building wake-enhanced modified Gaussian plume model. Model predictions using the Gaussian plume model unmodified, modified with field calculated dispersion parameters (the standard deviations of the profile as presented in the field study report), and modified with adjustments to the estimated plume centerline height

were also examined but are not tabulated here. Some of the results of these additional analyses are incorporated into the following discussions. This provides some contrast to the proposed model for the purpose of identifying potential improvements to the model.

2. RESULTS AND ANALYSES

2.1. *Overview*

Scatterplots of observed vs modeled concentrations are presented. They give an overall impression of model performance. Then the results of several key performance measures are presented. The primary interest here is in the differences between observed and modeled concentrations and their variation relative to the mean observed concentration. Comparisons relative to the mean observed concentration provide the most appropriate contrast among the category groupings. The linear correlation between observed concentrations and modeled concentrations are presented. Linear regression and model adjustment based on the calculated regression slope were made. The results of the key performance measures for the regression adjusted modeled concentrations are presented. Greatly improved performance would indicate that some linear adjustment to the proposed model is needed. Discussion of potential improvements to the model is provided. The variation among observed concentrations and among modeled concentrations for both between means of partitioned groups and the average variation within the partitioned groups are presented. The comparison of the variation for fully-partitioned groups should be related to the inherent limitations of a Gaussian plume model.

2.2. *Scatterplots*

Figures 1–3 present the scatterplots of observed concentrations vs predicted concentrations for both the proposed modified (with wake-enhanced dispersion parameters) and the unmodified model. The data are symbolized by their observed stability class. Scatterplots are a very simple way of obtaining a visual impression of overall model performance. These figures were examined for any obvious pattern to the model performance. Differences by stability class may be distinguished. The model predictions for DAEC and EOCR were represented by a few distinct values, which represent the partitioning among the categories by distance, stability class and release height. The model predictions for NGCl were not similarly limited because of added variation introduced by the variation of estimated plume rise.

In summary, the proposed wake-enhanced model predictions appeared to be better than the unmodified model predictions. Except for a linear factor, the wake enhanced model performance looked very good for DAEC and NGCl. Performance was not nearly as good for EOCR; however, it appears to be a great improvement in comparison to the unmodified model.

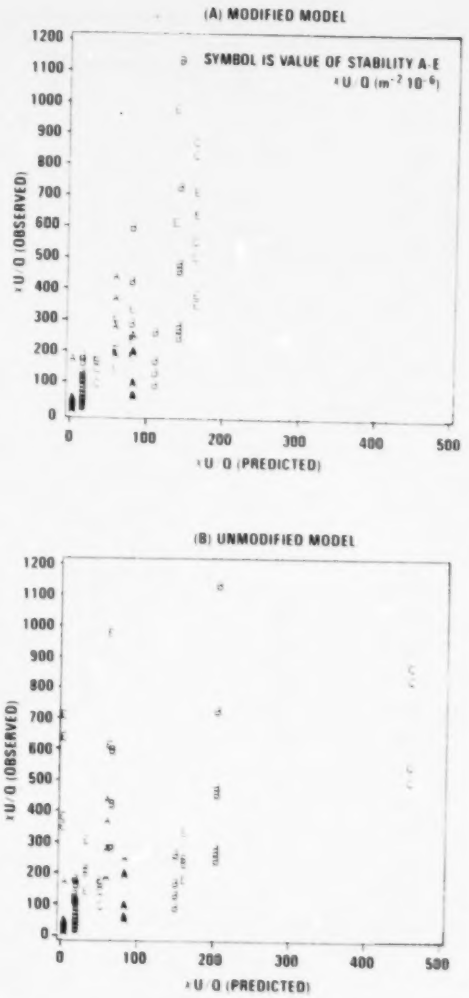


Fig. 1. Scatterplot of concentrations for DAEC. (A) Modified model; (B) unmodified model.

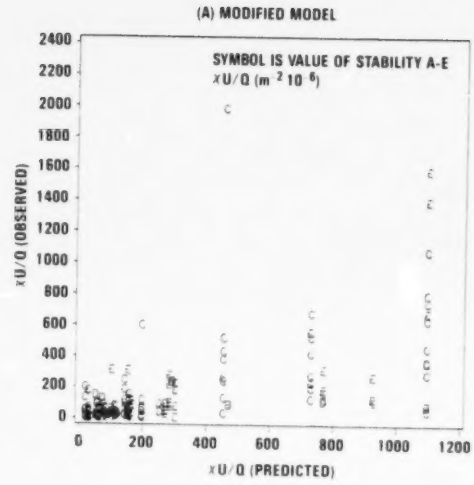
2.3. *Performance measures*

Tables 1(a), (b) and (c) present several measures of performance for the proposed modified model, for each study, based on differences between the model-predicted (P) and the observed (O) concentrations. In these tables, the value of N is the number of individual values included in the calculated statistic. The mean observed concentration is reported along with the measures defined as follows:

$MFE = (\overline{P-O})/\bar{O}$: mean fractional error

$FME = (\bar{P}-\bar{O})/(\bar{O})$: fractional mean error

$CV = (RMSE/\bar{O}) \times 100\%$: root-mean-square error ($RMSE$) coefficient of variation.



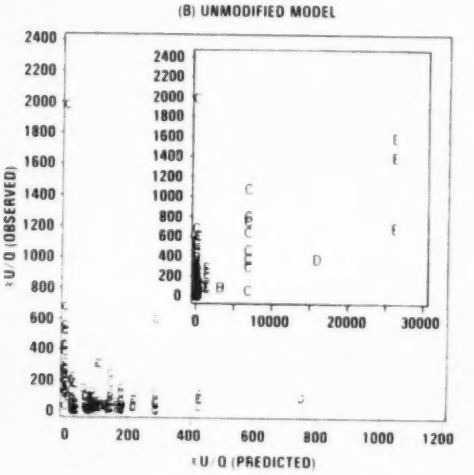
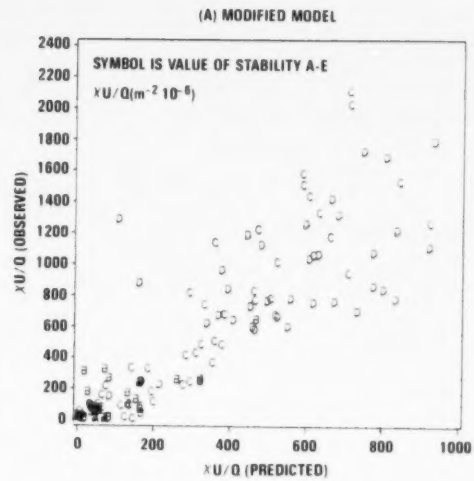


Fig. 2. Scatterplot of concentrations for EOCR. (A) Modified model; (B) unmodified model.



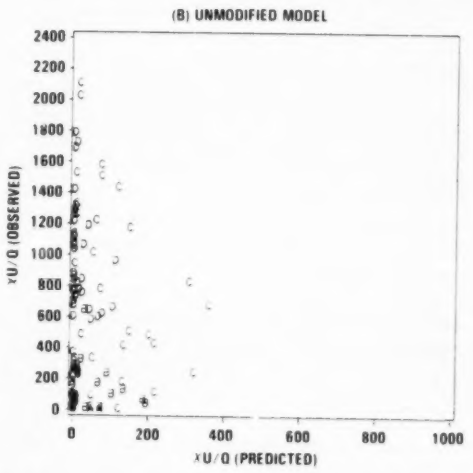


Fig. 3. Scatterplot of concentrations for NGCL. (A) Modified model; (B) unmodified model.

The mean fractional error (MFE) is a measure of the mean difference between the model-predicted and observed concentrations relative to the observed concentration. The fractional mean error (FME) is the difference between the mean model-predicted and the observed concentration (model bias) relative to the mean observed concentration. The calculated value of these two statistics are different depending on the variability among the individual differences relative to the observed concentration. The $RMSE$ coefficient of variation (CV) is a measure of model performance that includes both the effects of model bias and variability in performance relative to the mean observed concentration. Several other performance measures were evaluated along with the tabulated statistics. The following discussion reports some values for an adjusted CV where the model bias was factored out of the statistic. Measures of absolute value differences, and measures relative to the average of both model-predicted and observed concentration were evaluated. These other statistics were found to provide no information beyond that provided by the key measures reported here. This probably resulted from the fact that both the model-predicted concentrations and the observed concentrations had few extreme outliers within the partitioned groups.

The mean model-predicted concentration and the mean-observed concentration for DAEC [Table 1(a)] followed the same trends with changing groups by distance, stability class and release height. The overall CV with the bias factored out was 86%. These measures of model performance demonstrated good

Table 1(a). Measures of performance, DAEC

	N	Mean observed $\chi U/Q$ ($m^{-2}10^{-6}$)	Mean predicted $\chi U/Q$ ($m^{-2}10^{-6}$)	MFE	FME	CV (%)
By distance (km)						
0.3	37	391	114	−0.52	−0.71	97
1.0	39	102	25	−0.72	−0.75	101
By stability (class)						
A	26	116	39	−0.58	−0.66	115
B	28	236	68	−0.60	−0.71	119
C	8	414	98	−0.75	−0.76	102
E	14	393	106	−0.69	−0.73	94
By release height (m)						
0.0	22	339	87	−0.71	−0.74	83
23.5	30	149	60	−0.43	−0.60	140
45.7	24	272	63	−0.79	−0.77	114
Overall	76	243	68	−0.62	−0.72	112

Table 1(b). Measures of performance, EOCR

	N	Mean observed $\chi U/Q$ ($m^{-2}10^{-6}$)	Mean predicted $\chi U/Q$ ($m^{-2}10^{-6}$)	MFE	FME	CV (%)
By distance (km)						
0·068	40	434	800	2.94	0.84	135
0.386	41	91	200	6.15	1.20	175
0.794	44	44	95	5.24	1.16	182
1.2	24	51	62	3.41	0.22	137
1.6	24	46	44	1.71	−0.052	126
By stability (class)						
B	8	65	277	4.25	3.26	634
C	92	164	259	4.16	0.58	177
D	10	98	286	2.63	1.92	352
E	53	157	321	4.29	1.04	195
By release height (m)						
1	58	192	336	4.28	0.75	165
25	51	113	286	4.75	1.53	239
30	54	149	220	3.34	0.48	215
Overall	163	153	282	4.11	0.84	198

model sensitivity to the changing field conditions, which was found to be a large improvement in comparison to the unmodified model. Performance was not improved for model predictions using the lateral dispersion parameter calculated from the field profiles or with the effective plume centerline height assumed to be at ground level. The overall model CVs were unchanged and the model biases were 1.1 times and 0.9 times the value for the proposed model, respectively.

The mean model-predicted concentration and the mean-observed concentration for EOCR [Table 1(b)] followed somewhat different trends with changing groups. The differences were larger for stabilities B and D, both of which have a small number of values. These two groups are excluded from further discussions for this reason. The calculated MFEs were much larger than the FMEs for all groups. This indicated that there was much variation among the individual comparisons. The overall CV with the bias factored out was 179%. These measures of model performance demonstrated a less than desirable sensitivity to the changing field conditions; however, they represent improvement in comparison to the unmodified model. Performance was improved for model-predictions using the lateral dispersion parameters calculated from

Table 1(c). Measures of performance, NGC1

	N	Mean observed $\chi U/Q$ ($m^{-2}10^{-6}$)	Mean predicted $\chi U/Q$ ($m^{-2}10^{-6}$)	MFE	FME	CV (%)
By distance (km)						
0.05	17	809	578	−0.22	−0.29	45
0.061	12	664	278	−0.47	−0.58	99
0.0915	12	628	227	−0.60	−0.64	91
0.1	14	806	472	−0.34	−0.41	59
0.15	8	668	402	−0.30	−0.40	56
0.2	6	564	334	−0.26	−0.41	67
By stability (class)						
B	17	203	134	−0.32	−0.34	63
C	28	827	444	−0.37	−0.46	61
D	23	985	567	−0.38	−0.42	56
By release height (m)						
9.75	54	801	429	−0.37	−0.46	67
14.48	15	403	306	−0.33	−0.24	33
Overall	69	714	402	−0.36	−0.44	66

the field profiles. Performance was poorer with all effective plume centerline heights assumed to be at ground level. Their overall model *CV*s were 133 and 634%, respectively. Their overall model biases were 0.14 and 3.44 times the value for the proposed model, respectively.

The mean model-predicted concentration and the mean-observed concentration for NGC1 [Table 1(c)] followed the same trends with changing groups by distance, stability class and release height. The predicted concentrations for the 0.061 km and 0.0915 km distances were relatively lower because most of the cases had higher estimated plume centerline heights relative to the cases represented at the other distances. The overall *CV* with the bias factored out was 50%. These measures of model performance demonstrated good model sensitivity to the changing field conditions and represent a very large improvement in comparison to the unmodified model. Performance was improved for model-predictions using the lateral dispersion parameters calculated from the field profiles. The overall *CV* was unchanged; however, the model bias was 0.3 times the value for the proposed model. Performance was further improved by estimating the effective plume rise to be only two-thirds of the original value. The overall *CV* was unchanged; however, the model bias was 0.19 times the value for the proposed model.

2.4. *Linear correlation and regression*

Tables 2(a), (b) and (c) report measures of linear correlation and linear regression between the model-predicted and observed concentrations. Calculations

Table 2(a). Measures of linear correlation and regression, DAEC

	N	Correlation (Spearman)	Regression (slope)	FME	CV (%)
By distance (km)					
0.3	37	0.48	3.50	−0.018	58
1.0	39	0.72	3.49	0.15	52
By stability (class)					
A	26	0.55	2.41	0.20	94
B	28	0.71	3.30	0.049	81
C	8	0.87	4.24	−0.0053	30
E	14	0.79	3.73	−0.0038	45
By release height (m)					
0.0	22	0.90	3.90	0.0095	57
23.5	30	0.77	2.69	−0.076	101
45.7	24	0.90	3.74	0.15	47
Overall	76	0.78	3.50	0.017	67

Table 2(b). Measures of linear correlation and regression, EOCR

	N	Correlation (Spearman)	Regression (slope)	FME	CV (%)
By distance (km)					
0.068	40	0.21	0.52	0.037	97
0.368	41	0.25	0.44	0.029	116
0.794	34	0.33	0.45	0.034	123
1.2	24	0.15	0.75	0.092	131
1.6	24	0.051	0.74	0.30	122
By stability (class)					
B	8	0.90	0.14	0.41	125
C	92	0.62	0.57	0.10	138
D	10	0.22	0.28	0.19	73
E	53	0.62	0.54	−0.10	142
By release height (m)					
1	58	0.84	0.59	−0.040	119
25	51	0.62	0.38	0.023	93
30	54	0.52	0.49	0.28	183
Overall	163	0.65	0.52	0.045	143

Table 2(c). Measures of linear correlation and regression, NGC1

	N	Correlation (Spearman)	Regression (Slope)	FME	CV (%)
By distance (km)					
0.05	17	0.92	1.43	−0.022	30
0.061	12	0.85	2.25	0.058	58
0.0915	12	0.80	2.33	0.16	58
0.1	14	0.84	1.72	−0.007	34
0.15	8	0.55	1.68	−0.010	33
0.2	6	0.60	1.72	−0.019	32
By stability (class)					
B	17	0.43	1.18	0.22	61
C	28	0.93	1.92	−0.029	36
D	23	0.26	1.57	0.096	43
By release height (m)					
9.75	54	0.83	1.82	0.024	42
14.48	15	0.97	1.14	0.13	29
Overall	69	0.85	1.17	0.038	45

were made using SAS (1985) software. Statistical significance was presumed when calculated $\alpha < 0.01$; where 100α corresponds to the probability of obtaining a larger correlation or a larger regression coefficient value by chance alone (under the hypothesis that they are zero). The value of N is the number of individual values included in the calculated statistic. Correlation coefficients were calculated based on the usual Pearson product-moment correlation and the Spearman correlation of the ranks. Only the Spearman correlations are reported. They were found to be better indicators of performance because they were less influenced by outliers. A few situations were observed where the Pearson correlation was not significant in comparison to a significant Spearman correlation. The calculated regression coefficient is the usual least squares estimate of the linear regression of the observed concentration on the model-predicted concentration (slope). For these calculations, the intercept term in the regression analysis was suppressed (i.e. regression was forced through the origin). This was done because the objective was to assess the model performance after a purely linear change to the proposed model. The fractional mean error (FME) and the $RMSE$ coefficient of variation (CV) were recalculated for the linearly adjusted model performance. Regression analyses that find nearly the same coefficient over all the groups and find reduced FME and CV provide a good indication that there is a simple linear error in the proposed model-predicted and/or

the observed concentrations. Error in wind speed and/or tracer emission rate could similarly effect model performance measures. Otherwise, potential modifications to improve the proposed model are limited to changes to the dispersion parameters and/or the effective plume centerline height.

The correlations and regression coefficients for DAEC were found to be highly significant for all groups. Analyses of model predictions having the added assumption of plume height at ground level resulted in a slightly lower regression coefficient but did not result in better performance measures than for the proposed model. Analyses of model predictions based on the calculated field lateral dispersion parameters resulted in further significant improvement in the performance measures for stability E and both elevated release heights; however, their resulting regression coefficients were larger. This indicated that the lateral dispersion parameters (standard deviation of field distribution) may have overestimated the overall lateral plume spread.

The correlation coefficients for EOCR were found to be insignificant for distance groups. This indicates that the variations of model-predicted and observed concentrations were more significantly influenced by stability class or release height. The regression coefficients were all found to be significant for the proposed model. The overall regression model coefficient is 0.52 compared to the overall value of 0.96 for model-predicted concentrations using the field calculated lateral dispersion parameter. However, this modification to the proposed model did not significantly affect the calculated performance measures. This indicates that the field calculated lateral dispersion parameters accurately reflected the overall mean lateral plume spread; however, the variability among the individual concentrations relative to the mean concentration was not improved.

The correlation coefficients for NGCl were found to be highly significant for all groups except for distances 0.15 and 0.2 km, and stability D. All regression coefficients for the proposed model were found to be significant. Performance was found to be decreased for model-predicted concentrations having the field calculated lateral dispersion parameters. Model-predicted concentrations using the estimated plume centerline height adjusted to a value equal to two-thirds the original estimate were found to have model regression coefficients closer to 1. Overall the FME and CV values were -0.017 and 46%, respectively.

2.5. *Variability analyses*

Tables 3(a), (b) and (c) report the standard deviations among the proposed model-predicted and observed concentrations divided by their mean concentration (i.e. CV) calculated for groups by source–receptor distance (X), release height (HS), and stability class (STAB). The value of N is the number of individual values included in the calculated CV. Separate calculations were made for each X since source–receptor distances were not considered as a part of the model error. The G or NG under HS or STAB indicate whether the concentrations were grouped or not grouped by these categories. Thus, where there was grouping, the value N corresponds to the number of different groups. Note that N for the fully partitioned groups may not be as large as the product of (N for groups by HS) times (N for groups by STAB), since each stability class may not be represented for each release height. The 'between means' CV change from representing the entire sample of N individual values to representing N mean values weighted by their sample size. The 'average within' CV represents averages of each CV calculated first on concentrations within the N groups (i.e. pooled within the categories). The values of the 'between means' and

Table 3(a). Variability for DAEC

	X (km)	HS	STAB	N	Overall $\chi U/Q$ mean ($m^{-2}10^{-6}$)	Between means CV (%)	Average within CV (%)
(Observed)	0.3	NG	NG	37	391	70.1	70.1
		G	NG	3	391	36.7	70.0
		NG	G	4	391	45.5	58.1
		G	G	8	391	55.0	45.9
	1.0	NG	NG	39	102	85.9	85.8
		G	NG	3	102	28.8	88.4
		NG	G	4	102	71.6	71.0
		G	G	8	102	76.6	51.1
(Predicted)	0.3	NG	NG	37	114	33.4	33.4
		G	NG	3	114	20.4	25.8
		NG	G	4	114	29.6	15.3
		G	G	8	114	33.4	0.0
	1.0	NG	NG	39	25	101.0	101.0
		G	NG	3	25	4.27	94.4
		NG	G	4	25	99.0	4.01
		G	G	8	25	101.0	0.0

the 'average within' are identical for the ungrouped case because they are both based on all N individual values. Comparisons and contrasts among the CVs should show some important aspects of concentration variation. The observed 'between means' CV should show how the variation of observed mean concentration between groups is larger for the fully partitioned groups (i.e. approaches that for the individual values). The observed 'average within' CV should show how the variation within groups is smaller for the fully partitioned group (i.e. approaches that for inherent natural randomness). By definition, in absence of plume rise variation the model's predicted 'between means' CV for fully partitioned group means is the same as that for the individual values, while the 'average within' CV for fully partitioned groups is zero. There were some differences for NGCl due to added variation for plume rise.

Table 3(a) summarizes the analyses for DAEC. For 'between means' the CV values for groups by HS only were lowest; this indicates that the differences in HS were less of a factor in the variation among concentrations than the differences in STAB. For 'average within' the CV values indicate that groups by STAB have less variability than those by HS.

The EOCR analyses are summarized in Table 3(b). For 'between means' the observed CV values for groups partitioned by either HS or STAB categories were much lower than groups without any partitioning or with full partitioning by both categories. This indicated that both HS and STAB were significant factors. The predicted CV values for partitioning by HS were lowest (except for the nearest distance), indicating that differences in HS were far less of a factor in model variability than the differences in STAB. The observed 'average within' CV values were

Table (3b). Variability for EOCR

	X (km)	HS	STAB	N	Overall $\chi U/Q$ mean ($m^{-2}10^{-6}$)	Between means CV (%)	Average within CV (%)
(Observed)	0.068	NG	NG	40	434	98.5	98.5
		G	NG	3	434	36.8	89.9
		NG	G	4	434	23.0	91.9
		G	G	11	434	63.3	67.1
	0.386	NG	NG	41	91	118.0	118.0
		G	NG	3	91	31.6	97.4
		NG	G	4	91	24.2	109.0
		G	G	11	91	42.0	98.0
	0.794	NG	NG	34	44	130.0	130.0
		G	NG	3	44	33.6	114.0
		NG	G	4	44	46.8	106.0
		G	G	10	44	66.5	102.0
	1.2	NG	NG	24	51	135.0	135.0
		G	NG	3	51	61.4	113.0
		NG	G	3	51	40.8	136.0
		G	G	8	51	88.3	79.5
	1.6	NG	NG	24	46	109.0	109.0
		G	NG	3	46	45.3	90.3
		NG	G	3	46	24.4	105.0
		G	G	8	46	68.6	90.4
(Predicted)	0.068	NG	NG	40	800	32.6	32.1
		G	NG	3	800	26.9	16.9
		NG	G	4	800	11.3	31.6
		G	G	11	800	32.1	0.0
	0.368	NG	NG	41	200	32.3	32.3
		G	NG	3	200	7.15	32.3
		NG	G	4	200	30.9	10.6
		G	G	11	200	32.3	0.0
	0.794	NG	NG	34	95	51.5	51.5
		G	NG	3	95	8.2	52.9
		NG	G	4	95	51.3	4.74
		G	G	10	95	51.5	0.0
	1.2	NG	NG	24	62	58.4	58.4
		G	NG	3	62	6.8	60.9
		NG	G	3	62	58.2	3.59
		G	G	8	62	58.4	0.0
	1.6	NG	NG	24	44	65.5	65.5
		G	NG	3	44	7.4	68.5
		NG	G	3	44	65.3	2.95
		G	G	8	44	65.5	0.0

Table 3(c). Variability for NGCl

	X (km)	HS	STAB	N	Overall $\chi U/Q$ mean ($m^{-2}10^{-6}$)	Between means CV (%)	Average within CV (%)
(Observed)	0.05	NG	NG	17	809	61.0	61.0
		G	NG	2	809	0.52	58.4
		NG	G	4	809	44.4	44.3
		G	G	5	809	47.2	39.9
	0.061	NG	NG	12	664	115.0	115.0
		G	NG	2	664	56.8	82.9
		NG	G	3	664	74.6	68.1
		G	G	5	664	111.0	50.5
	0.0915	NG	NG	12	628	96.8	96.8
		G	NG	2	628	55.3	73.2
		NG	G	3	628	66.6	70.1
		G	G	5	628	93.2	51.9
	0.1	NG	NG	14	806	61.1	61.1
		G	NG	2	806	1.17	63.8
		NG	G	3	806	37.3	47.2
		G	G	4	806	38.3	51.0
	0.15	NG	NG	8	668	47.1	47.1
		G	NG	2	668	2.21	47.6
		NG	G	3	668	37.0	30.6
		G	G	5	668	37.9	35.8
	0.2	NG	NG	6	564	51.5	51.5
		G	NG	2	564	6.68	48.8
		NG	G	2	564	31.7	50.7
		G	G	4	564	34.2	68.9
(Predicted)	0.05	NG	NG	17	578	47.4	47.4
		G	NG	2	578	14.7	45.4
		NG	G	4	578	38.3	27.8
		G	G	5	578	38.4	8.3
	0.061	NG	NG	12	278	112.0	112.0
		G	NG	2	278	56.5	66.7
		NG	G	3	278	71.8	63.8
		G	G	5	278	103.0	34.9
	0.0915	NG	NG	12	227	114.0	114.0
		G	NG	2	227	55.0	69.3
		NG	G	3	227	73.0	69.6
		G	G	5	227	104.0	36.9
	0.1	NG	NG	14	472	48.8	48.8
		G	NG	2	472	20.1	48.9
		NG	G	3	472	35.5	33.05
		G	G	4	472	37.2	1.62
	0.15	NG	NG	8	402	29.5	29.5
		G	NG	2	402	8.8	30.8
		NG	G	3	402	26.2	14.4
		G	G	5	402	28.5	10.8
	0.2	NG	NG	6	334	32.8	32.8
		G	NG	2	334	11.7	34.5
		NG	G	2	334	18.8	31.0
		G	G	4	334	22.5	37.8

considerably larger than the model-predicted values.

Table 3(c) summarizes the analyses for NGCl. For the 'between means', the CV values for partitioning by HS were very much lower than for the other groupings. CV values for groups partitioned by STAB are only slightly more reduced than those partitioned both by HS and STAB. Thus, differences in HS were far less of a factor in variability among both the model-predicted and the observed concentrations than the differences in STAB. The closeness between the CV values for the observations and those for the proposed model indicate that the model performance may properly reflect the variability in the observed concentrations. The 'average within' CV values were similar to the model-predicted values.

The variability analyses for DAEC and NGCl showed both the model-predicted and the observed concentrations were less affected by source height than by stability classification (i.e. the variation due to source height is relatively less than that due to stability class and the observed 'natural randomness' not accounted for by the model). The model categories by source–receptor distance, source height and stability class apparently account for nearly half of the observed

variation among concentrations (i.e. see reduced 'average within'). The observed *CV*s among fully partitioned groups were lower than 50%, which represents a reasonable inherent limitation for the performance of a Gaussian plume model. The variability analyses for EOCR showed the model-predicted concentrations were less affected while the observed concentrations were most affected by source height in comparison to stability class. The model categories apparently accounted for less than half of the observed variation among concentrations. The observed *CV* among fully partitioned groups were nearly 100%, which represents less than desirable performance.

3. SUMMARY AND CONCLUSIONS

Gaussian plume models perform best when estimating mean concentrations over time where mean values of the input parameters are representative. For these studies, the variable model input parameters were limited to stability class, emission rate and wind speed. There are inherent uncertainty and limitation to a discrete stability classification system. The stability class is designed to classify the overall rate of plume dispersion. Stable classes reflect a slower rate of plume growth in comparison to that for unstable classes. However, the stable class EOCR cases apparently had larger overall plume growth in comparison to many of the neutral and unstable classes among all the studies as a result of larger meander in wind direction. A Gaussian plume model can perform well so long as the wind meander is properly incorporated into the plume dispersion parameters. Effects for wind meander were not modeled here. For EOCR, model-predicted concentrations were significantly improved when the calculated field dispersion parameters were used. Mean model-predicted ground-level centerline concentrations were quite comparable to mean observed concentrations while the *CV* was greatly reduced but remained high at a value near 100%. The large variability for EOCR probably reflects the non-representativeness of the standard deviation of the plume profile in calculating the overall plume spread. Cases having large wind meander probably tend to be characterized better by a non-Gaussian concentration distribution. This probably explains why *CV* values for EOCR were near 100%, while they were near 50% for DAEC and NGCl. Actual measured distributions which accurately reflect case specific plume meander and dispersion would be needed to improve upon the stability classification system.

The observed emission rates and observed wind speeds have definite limits to their accuracy and representativeness. The field emission rates were designed to be fairly constant throughout each sample period for measured concentrations. The wind speed was somewhat variable during each sample period. The observed mean wind speed was measured from an instrumental tower nearby the source. The temporal variability in wind speed should not be a significant source of model error provided it was randomly distributed about its mean value and provided the important atmospheric processes were Reynolds number independent. The spatial representativeness of the mean wind speed was somewhat questionable, considering the likely wind shear throughout the source–receptor region. Model error in the estimated wind speed at release height (important to initial source dilution) may be significant. Model error in the estimated wind speed has an added importance for NGCl since plume rise was estimated.

This study provides an in-depth evaluation of the variability and performance associated with a simple Gaussian plume model, field observations and their differences for ground-level plume centerline concentrations in the wake of a building. The results are particularly meaningful since the field measured concentrations were partitioned into sizeable groups by source–receptor distance, release height and stability class. Model error and variability due to the 'off centerline' factor were absent since only centerline values were compared. This framework provided a meaningful quantitative evaluation of model performance.

The comparisons between mean concentrations and coefficients of variation among concentrations indicate differences in the overall manner of model performance. The values of the mean and *CV* among field observations and those among the proposed model predictions were more uniform than among the unmodified model. The variability among the unmodified model predictions was larger than among the observations, which suggests that the model introduced unreal variation. The variability among the modified model predictions was smaller than for the observations, which suggests that the model could be refined further. Additional model factors are needed to realize the variability observed in the field. Present model factors appear to be deficient by 100% of the mean concentrations.

The comparisons between correlation coefficients indicate the difference in the degree of linearity between observed concentrations and the model predictions. The correlation coefficients for both the DAEC study and the NGCl study were very significant ($\alpha < 0.01$) for the proposed model; when the measured lateral dispersion parameters were incorporated into the model, most correlation coefficients were slightly higher for the DAEC study and slightly lower for the NGCl study. Correlations for the EOCR study were not as significant; when the measured lateral dispersion parameters were incorporated in the model, the correlations were higher.

The mean error overall values for each study represented the model bias. The fractional mean error was best for comparing the estimated bias among several groups of models. Both the mean error and the fractional mean error are insensitive to the variation among the individual error values. The *RMSE* coef-

ficient of variation is a very good measure for quantifying the overall magnitude of individual error values. The *RMSE* coefficient of variation adjusted for bias or adjusted for regression best represented reasonable estimates of error due to inherent variability among observations that is unexplainable by the model. These coefficients were found to be very useful measures for comparing the performance among several models.

The results here are in support of the earlier qualitative evaluation of the wake-enhanced dispersion method for estimating pollution concentrations downwind of influencing buildings (see Model I, Huber, op. cit.). A more specific conclusion may now be drawn for each study. For DAEC, the predictions were consistently a factor of 3.5 lower than observations; however, the model sensitivity to variation among the observations is very good. The tested reasonable adjustment to the model did not result in any better performance. The model underestimation cannot be explained. For EOCR, the predictions are on the average nearly a factor of two higher than observations. The model sensitivity to variation among the observations is primarily limited by the effects of wind meander. The use of field dispersion parameters resulted in great improvement to the model. For NGCI, predictions are consistently near a factor of 1.5 lower than observations. A reduction to modeled plume rise provides an appropriate correction. The model sensitivity to variation among the observations is very good. Overall, for groups with reduced measures of mean error, the variability among errors was reduced to values between 50 and 100% of the mean concentration, which appears here to represent the inherent limitation of the proposed simple Gaussian plume model. Thus, performance for this proposed model may only be further improved by examining the cause of overall mean error. Otherwise, additional variables for characterizing dispersion in the wake of buildings are required as model inputs.

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